# Big Bang Nucleosynthesis as a Precision Probe

## Heavy Neutral Leptons, Primordial Black Holes, and Others

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Based on:

- 2507.12290 (PRD) with P. S. Bhupal Dev & Xun-Jie Xu
- 2509.05618 (JCAP) with Xun-Jie Xu

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# Overview

This talk is based on the following two papers:

1. arXiv:2507.12270: *No Hiding in the Dark: Cosmological Bounds on Heavy Neutral Leptons with Dark Decay Channels*, Phys.Rev.D **113** (2026) 6, 063532
   Collaborators: P. S. Bhupal Dev & Xun-Jie Xu.

2. arXiv:2509.05618: *Primordial Black Holes Evaporating before Big Bang Nucleosynthesis*, *JCAP* **02** (2026) 063.
   Collaborator: Xun-Jie Xu.

# Outline

# 1.1 Nuclear Reaction Network during BBN

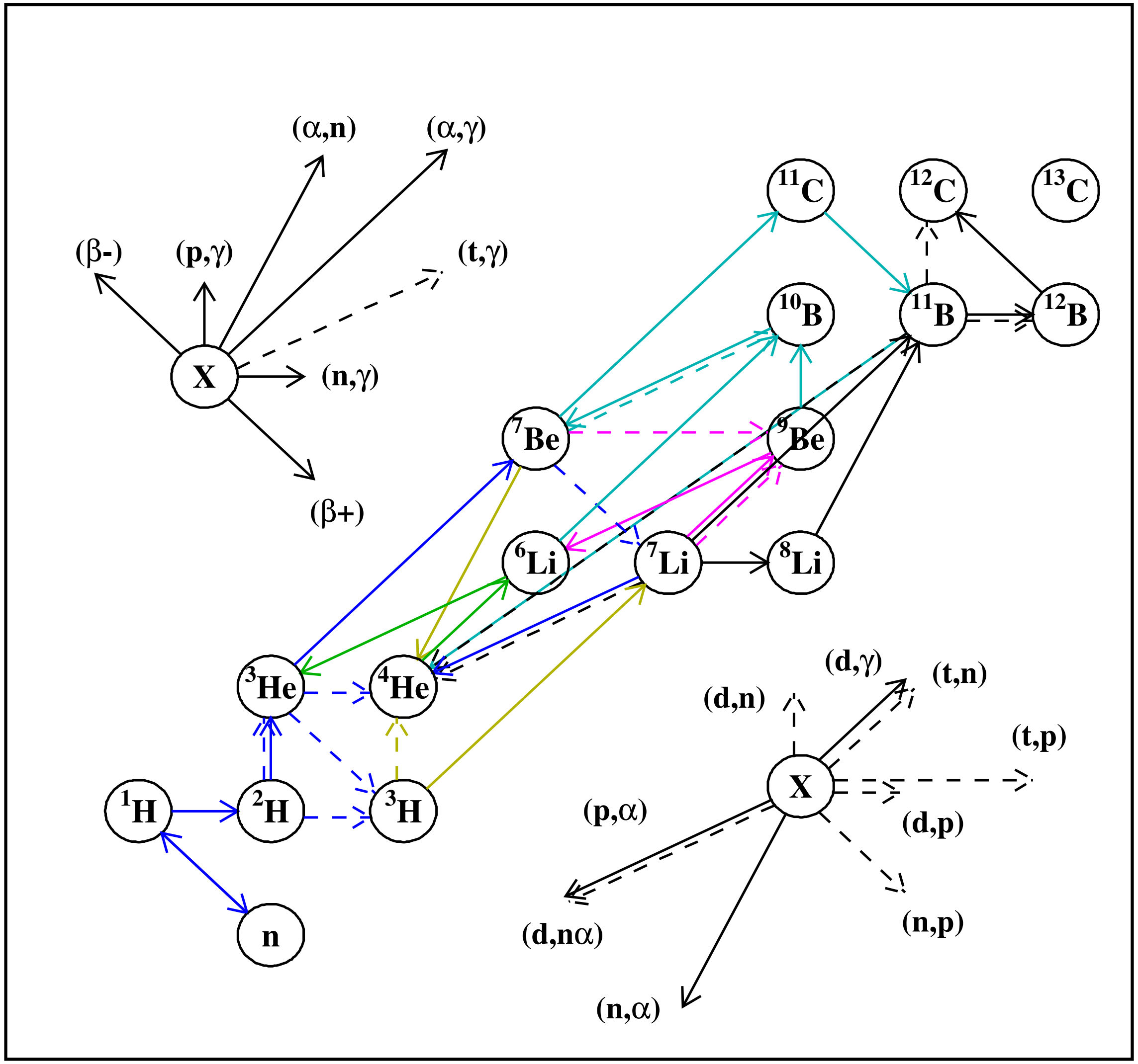



Figure 1: Reaction network for BBN. (Credits: Fig. 22 of Ref. (Pitrou et al. 2018))

- BBN **STARTS FROM** $p$ and $n$;
- Light elements are the most successful predictions of BBN;
- BBN is sensitive to some new physics!

# 1.2 Modern BBN Results

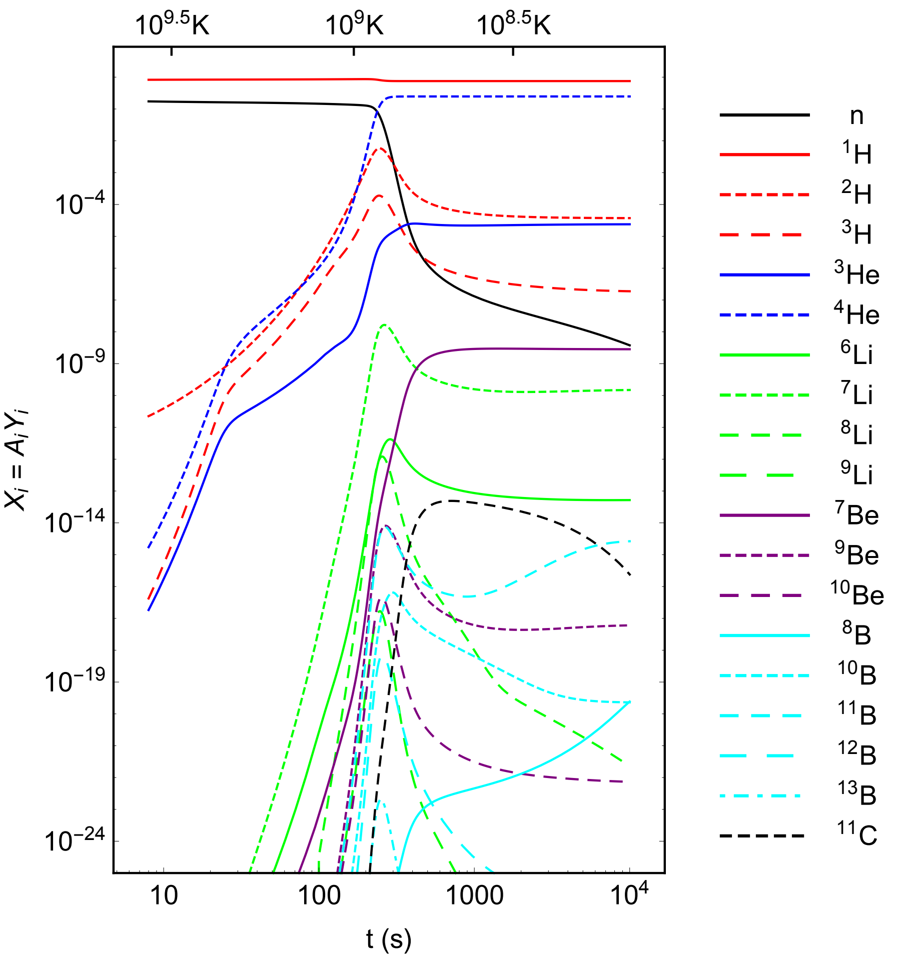



Figure 2: Predicted abundances of light elements from BBN. (Credits: Left of Fig. 25 of Ref. (Pitrou et al. 2018))

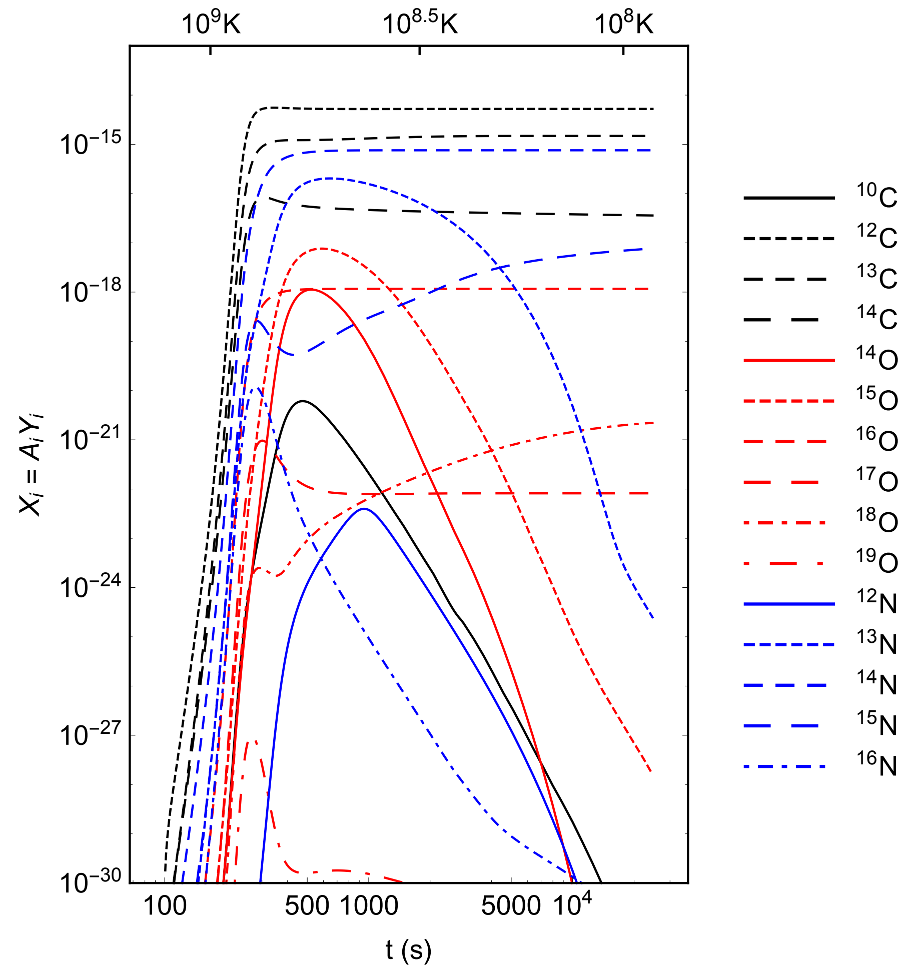
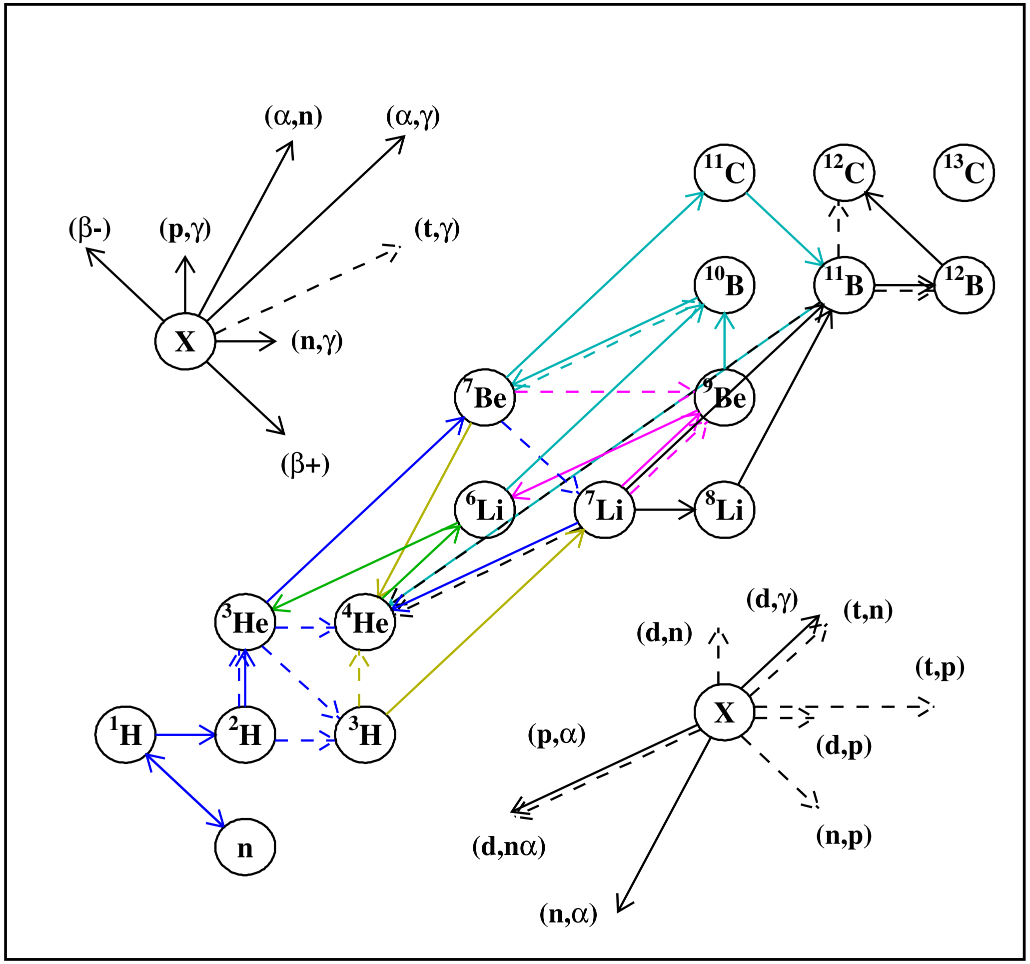



Figure 3: Predicted abundances of heavier elements from BBN. (Credits: Right of Fig. 25 of Ref. (Pitrou et al. 2018))

# 1.3 How New Physics Affects BBN?




- **Affecting the ingredients:** $\boldsymbol{X_n}$;
- **Affecting the background:** $\boldsymbol{H}$, $\boldsymbol{N_{\mathrm{eff}}}$...
- Affecting the nuclear reactions...
- Affecting the results of BBN...

# Outline

# 2.1 $\nu$SM: For Nonzero Neutrino Masses

- The SM is successful but **incomplete**!
- In the SM, only left-handed neutrinos are included, which are massless.
- Neutrino oscillation experiments have shown that neutrinos have nonzero masses, which provides a convincing evidence for physics beyond the SM (BSM).
- Adding RHNs:

$$\mathcal{L} \supset -\bar{\nu}_L m_D N_R - \frac{1}{2}\bar{\nu}_R^{\rm c} m_N N_R + \text{h.c.}$$

- Nonzero and tiny neutrino masses from Type-I seesaw:

$$m_\nu \simeq -m_D m_N^{-1} m_D^{\rm T}.$$

- Mixing in Type-I seesaw:

$$|U_{\alpha N}|^2 \approx \frac{m_\nu}{m_N} \text{ (a.k.a. the seesaw line).}$$

- RHNs can interacted with other SM particles via the mixing with SM neutrinos!

# 2.2 Heavy Neutral Leptons: Free $U_{\alpha N}$

- If we do not restrict ourselves to the Type-I seesaw, the RHN-like particles are also well-motivated and are usually called **Heavy Neutral Leptons (HNLs)**.

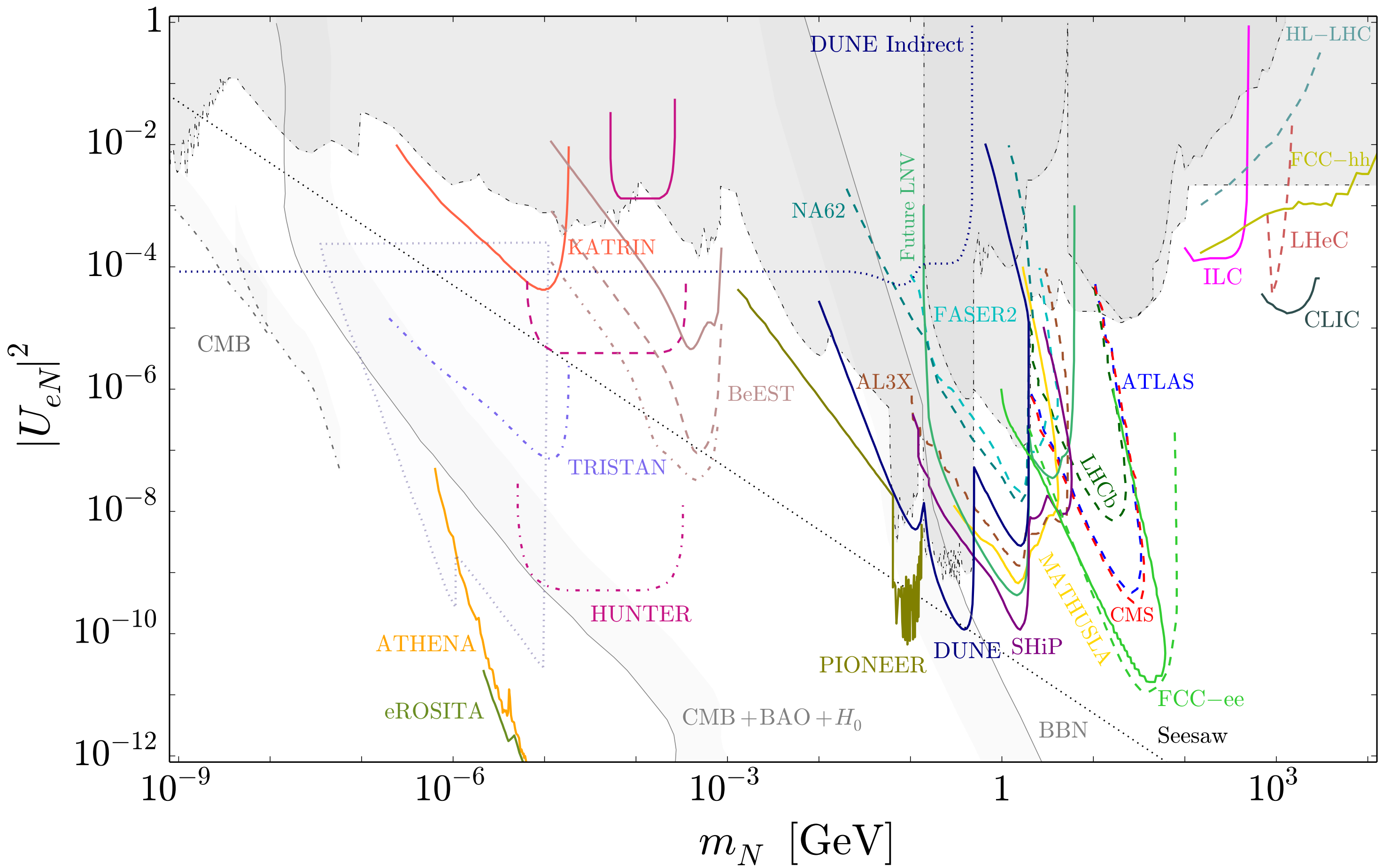



Figure 4: Parameter space for HNLs. (Credits: Fig. 1 of https://www.hep.ucl.ac.uk/~pbolton/plots.html)

# 2.3 HNL Decaying at BBN

- If HNLs decay at the time of BBN...

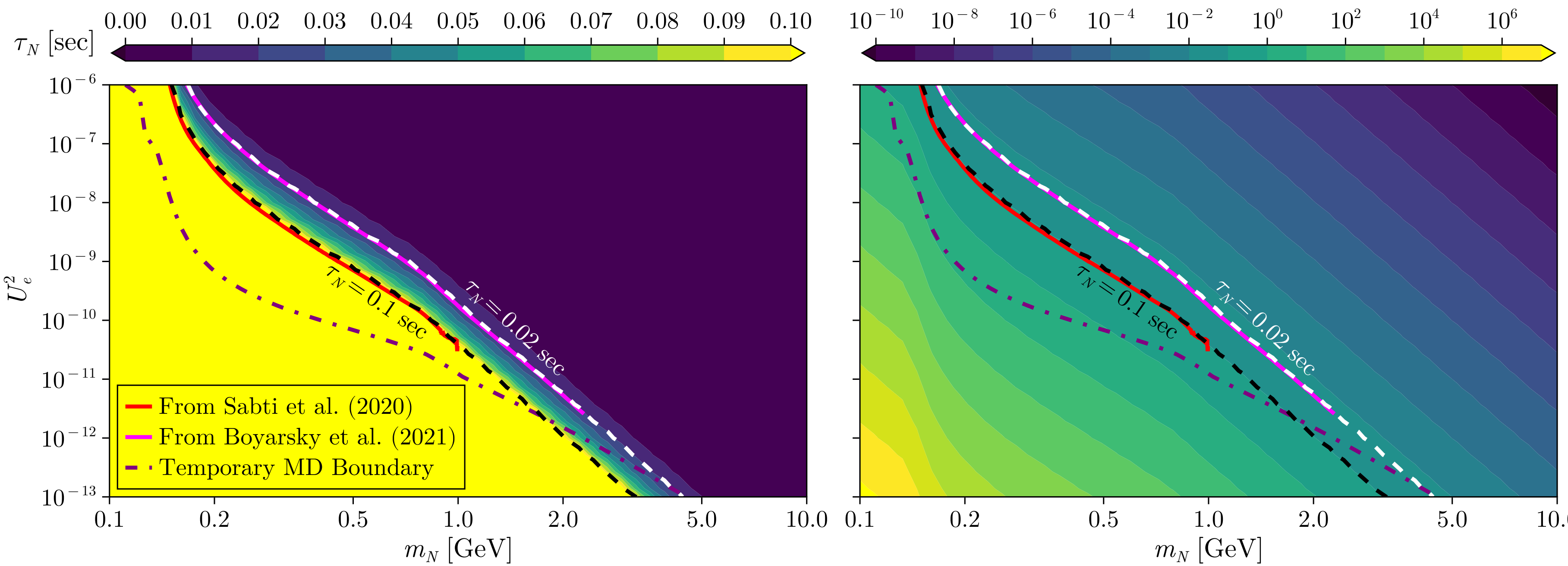



Figure 5: Lifetime of HNLs.

- Influence on BBN processes is inevitable!

# 2.4 Meson-Driven $n$–$p$ Interconversion

Mesons produced from HNL decays:

- $N \to e^{\pm}\pi^{\mp}$
- $N \to \nu_e \pi^0$
- $N \to e^{\pm}K^{\mp}$

Meson-driven $n$–$p$ interconversion (*e.g.*, pion-driven):

- $\pi^+ + n \to p + \pi^0$,
- $\pi^- + p \to n + \pi^0/\gamma$.

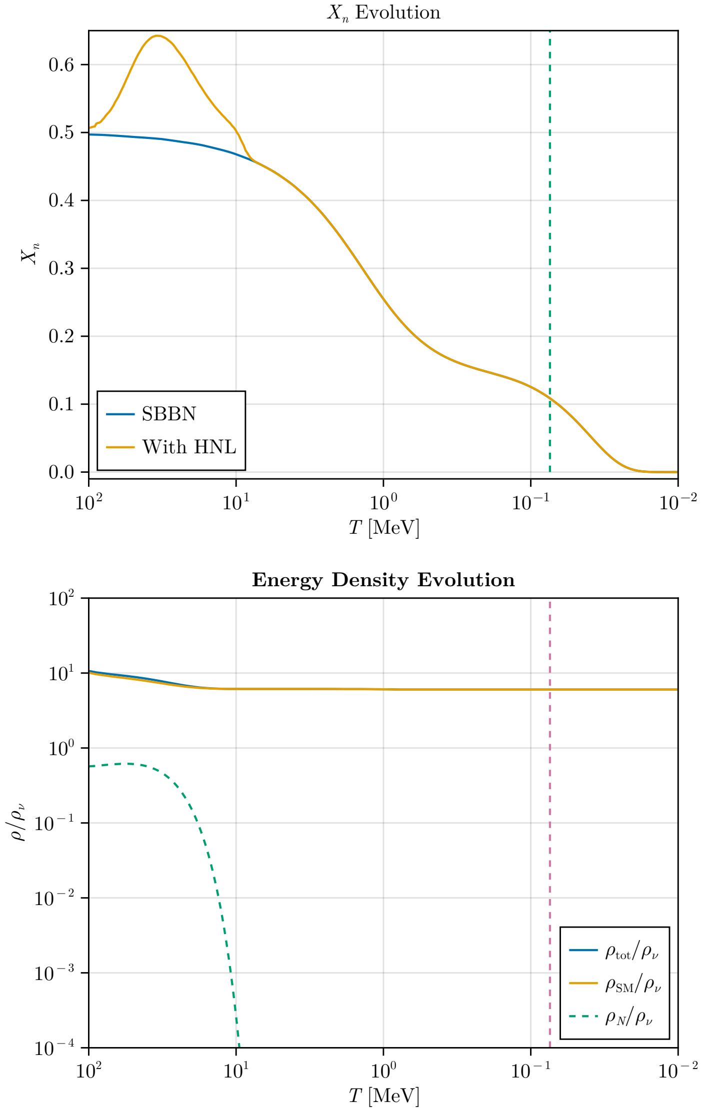



Figure 6: $m_N = 1$ GeV, $|U_{eN}|^2 = 10^{-4}$

# 2.5 Dark Decay Channels of HNLs

- Moreover, we can assume that HNLs have **dark decay channels**...
- For dark radiations as the decay products of HNLs:

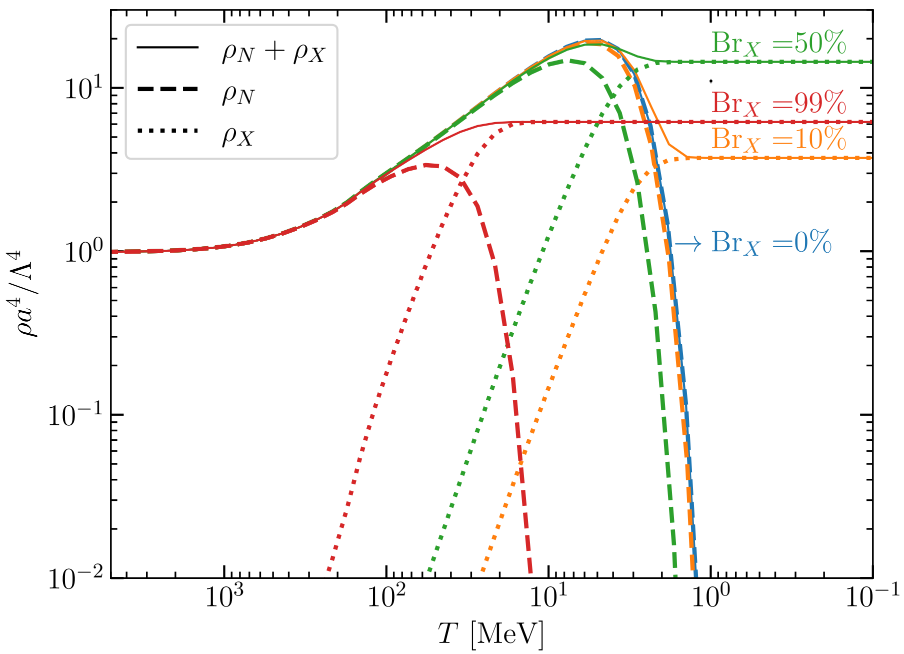



Figure 7: Different branching ratios of HNL decays into dark radiations.

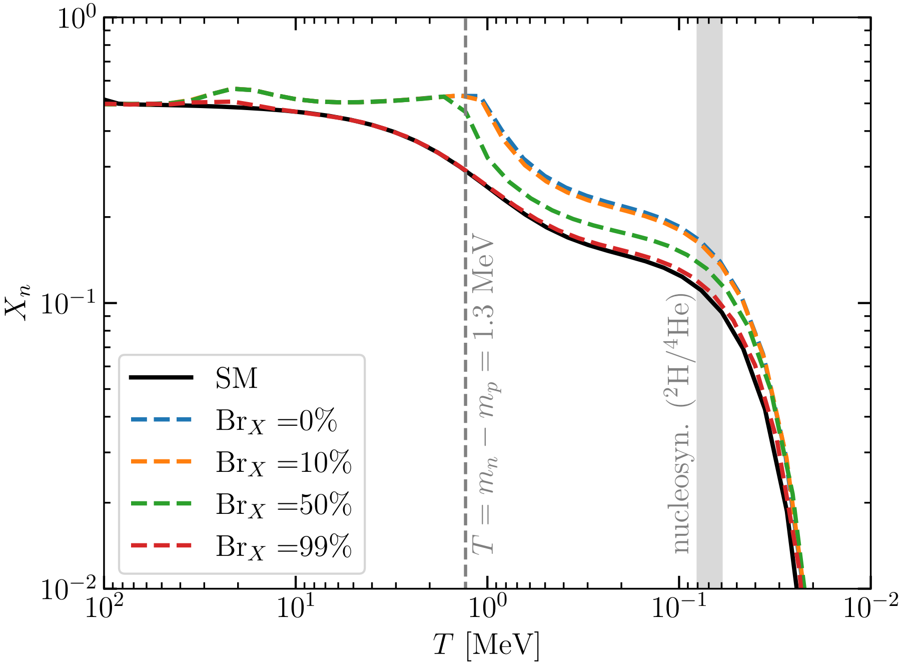



Figure 8: The corresponding Influences on the evolution of $X_n$.

# 2.6 Parameter Space Scanning

- Dark radiations from HNL decays can also change $N_{\rm eff}$ constrained by the cosmic microwave background (CMB) observations.
- The joint constraints from $Y_{\rm P}$ and $\Delta N_{\rm eff}$:

$$\chi^2 = \left[\frac{\Delta N_{\rm eff}^{\rm (CMB)}}{\sigma_{N_{\rm eff}^{\rm (CMB)}}}\right]^2 + \left[\frac{\Delta Y_{\rm P}}{\sigma_{Y_{\rm P}}}\right]^2 .$$

- **No "hiding in the dark"!**
- Most lab-relevant mixings stay cosmologically disfavored!

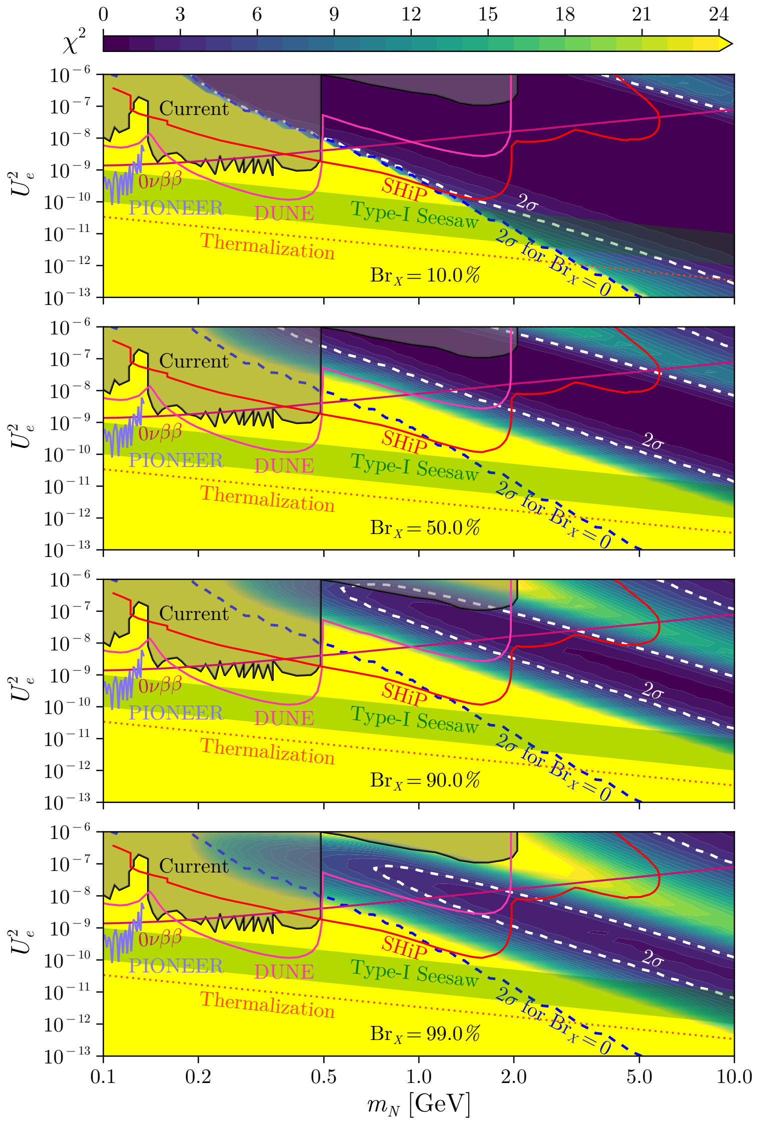



Figure 9: $\chi^2$ scanning for the parameter space of HNLs with different branching ratios into dark radiations.

# Outline

# 3.1 A Brief Introduction to Primordial Black Holes

- Black holes that are formed in the early Universe are called primordial black holes (PBHs).
- The mass of PBHs could range from the Planck mass ($M_{\rm Pl} \approx 2.18 \times 10^{-5}$ g) to millions of solar mass ($M_{\odot} \approx 1.99 \times 10^{33}$ g).

$$t_{\rm f} \approx \frac{m_{\rm PBH}^{(\rm f)}}{\gamma m_{\rm Pl}^2} \quad \text{with} \quad \gamma \approx 0.2.$$

- Hawking radiation: PBHs can evaporate by emitting Hawking radiation, which is a thermal radiation with the temperature of

$$T_{\rm PBH} = \frac{m_{\rm Pl}^2}{8\pi M_{\rm PBH}}.$$

- The smaller the mass of a PBH, the higher the temperature and thus the faster the evaporation!

# 3.1 A Brief Introduction to Primordial Black Holes

- Lifetime of PBHs:

$$\tau_{\mathrm{PBH}} = \frac{M_{\mathrm{PBH}}^{((\mathrm{f}))^3}}{3N_{\mathrm{PBH}}(T_{\mathrm{PBH}})m_{\mathrm{Pl}}^4} \quad \text{with} \quad N_{\mathrm{PBH}}(T_{\mathrm{PBH}}) = \frac{27}{4} \times \frac{N_\rho(T_{\mathrm{PBH}})}{30720\pi}.$$

- Evolution of PBHs:

$$M_{\mathrm{PBH}(t)} = M_{\mathrm{PBH}}^{(\mathrm{f})}\left(1 - \frac{t - t_{\mathrm{f}}}{\tau_{\mathrm{PBH}}}\right)^{\frac{1}{3}} \quad \text{for} \quad t \in [t_{\mathrm{f}}, t_{\mathrm{f}} + \tau_{\mathrm{PBH}}].$$

- Key temperatures for PBHs:

$$T_{\mathrm{f}} = 1.4 \times 10^{11}\ \mathrm{GeV}\left(\frac{10^9\ \mathrm{g}}{M_{\mathrm{PBH}}^{(\mathrm{f})}}\right)^{\frac{1}{2}},$$

$$T_{\mathrm{e}} = 1.8\ \mathrm{MeV}\left[\frac{10.75}{N_\rho(T_{\mathrm{e}})}\right]^{\frac{1}{4}}\left[\frac{10^9\ \mathrm{g}}{M_{\mathrm{PBH}}^{(\mathrm{f})}}\right]^{\frac{3}{2}}.$$

# 3.2 Overview of Constraints on PBHs

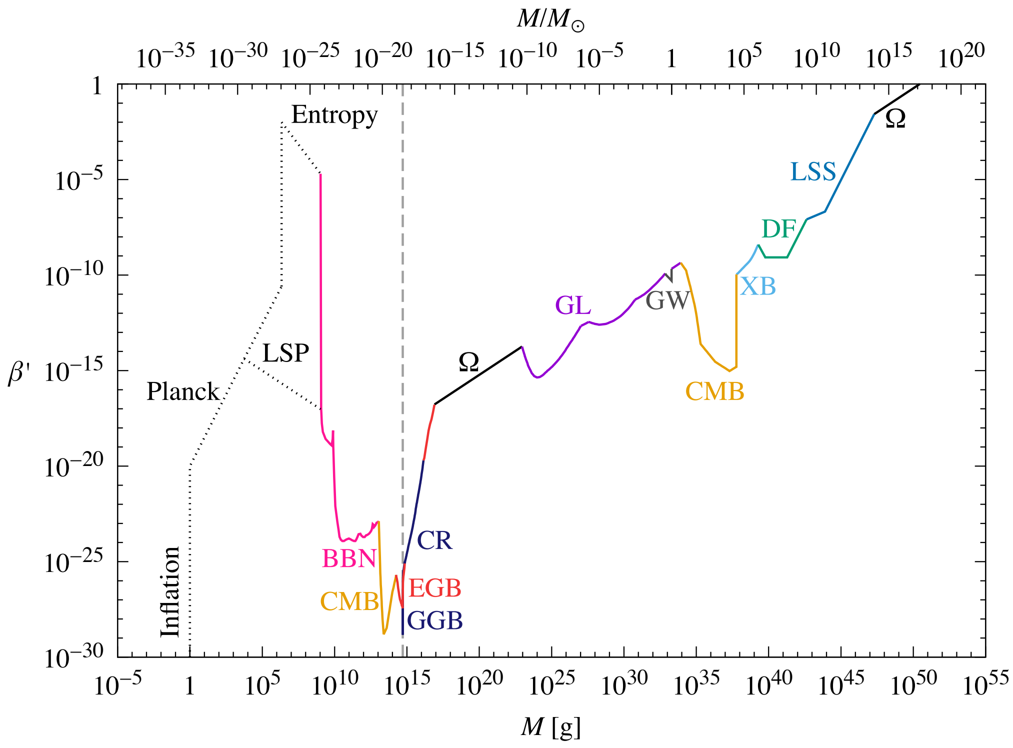



Figure 10: Overview of constraints on PBHs. (Credits: Fig. 18 of Ref. (Carr et al. 2021))

- Abundance of PBHs at formation:

$$\beta = \frac{\rho_{\text{PBH}}^{(\text{f})}}{\rho_{\text{tot}}^{(\text{f})}}.$$

- Reduced version of $\beta$:

$$\beta' = \gamma^{\frac{1}{2}} \beta \left( \frac{N_\rho(T_\text{f})}{106.75} \right)^{-\frac{1}{4}} \left( \frac{h}{0.67} \right)^{-2}.$$

# 3.3 How PBHs Affect BBN?

1. **Modifying the background of BBN**;
2. **Modifying the ingredients of BBN**;
3. Modifying the products of BBN.

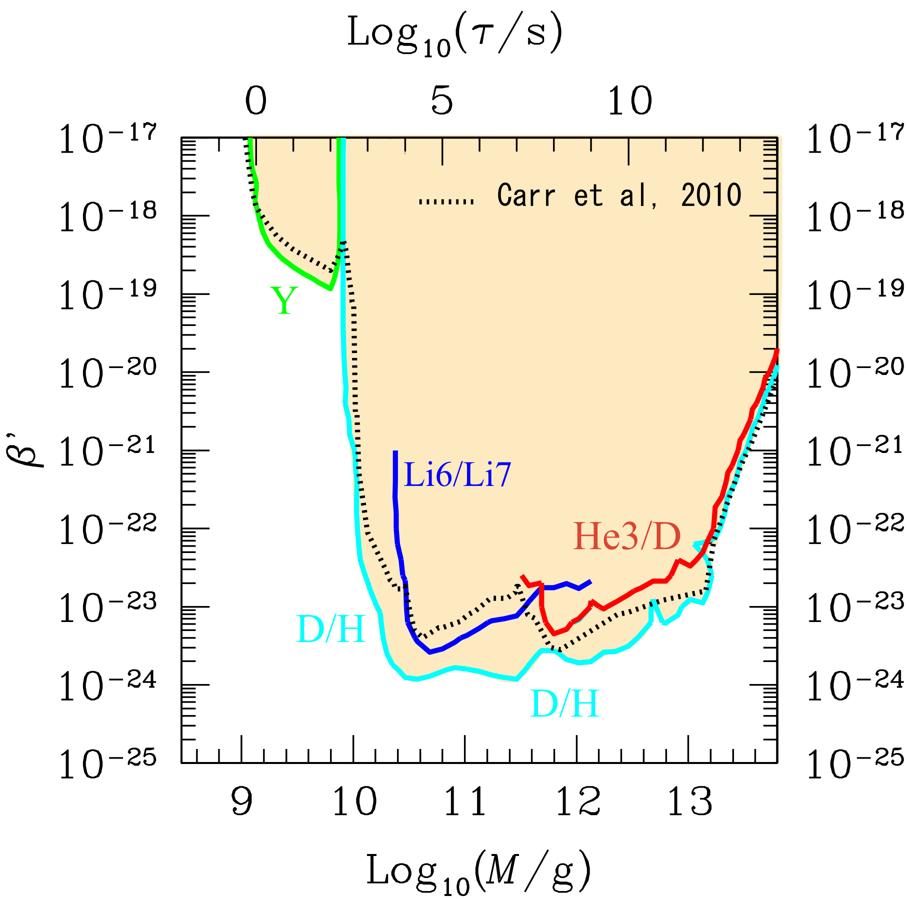



Figure 11: Constraints on PBHs from BBN. (Credits: Fig. 5 of Ref. (Carr et al. 2021))

# 3.4 Modifying the Background of BBN

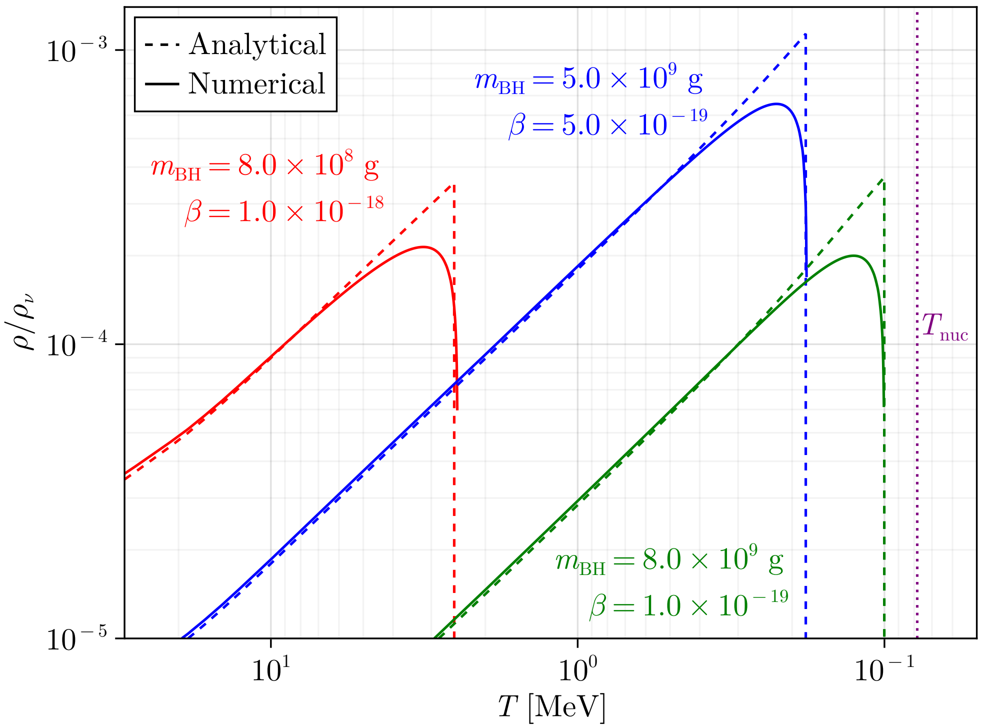



Figure 12: Energy density evolution of PBHs and radiation.

- Constrained by $N_{\rm eff}$:

$$\Delta N_{\rm eff} \lesssim 0.044 \times \frac{\beta}{10^{-16}} \left( \frac{m_{\rm PBH}^{(\rm f)}}{10^9 \text{ g}} \right),$$

- Here 0.044 is beyond the current sensitivity of BBN and CMB observations!

# 3.5 Modifying the Ingredients of BBN

- Similar to the case of HNLs.
- Mature code for Hawking radiation: `BlackHawk` (Arbey and Auffinger 2019, 2021).
- Hadronization code: `PYTHIAv8` (Bierlich and others 2022)

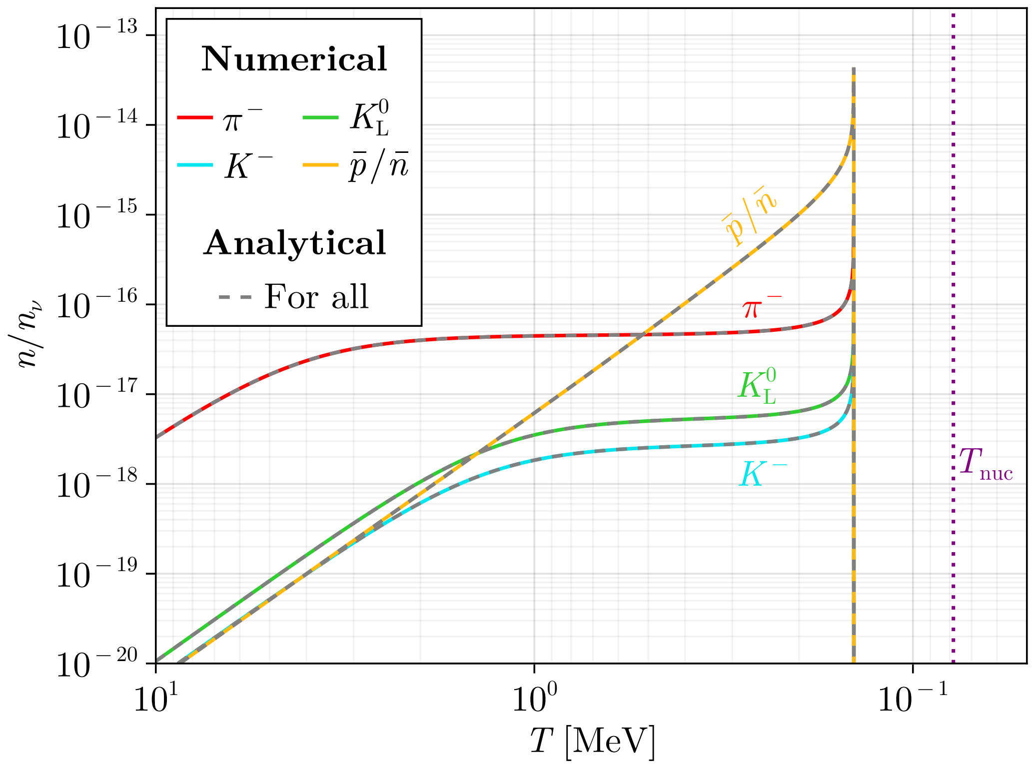



Figure 13: Hadrons from PBHs.

# 3.6 Effects on $X_n$ Evolution

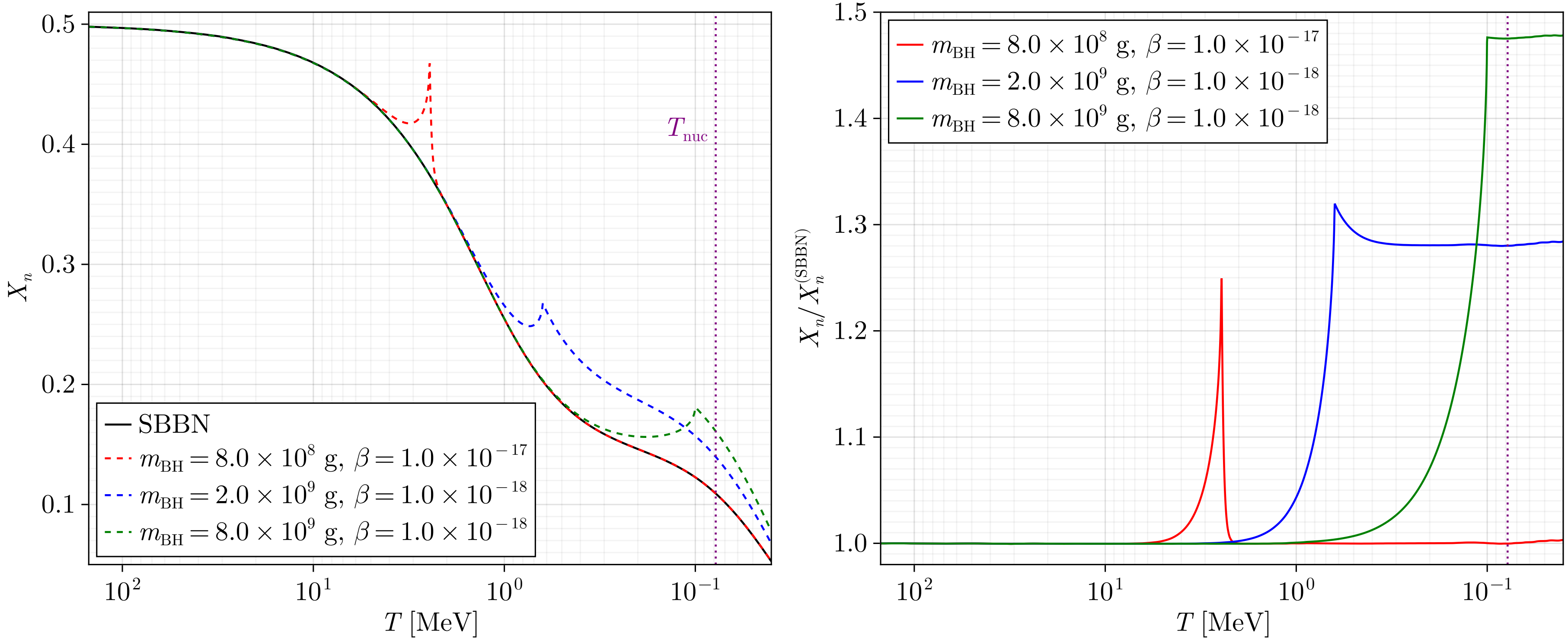



Figure 14: Influence on $X_n$ evolution from PBHs.

# 3.7 Scanning the Parameter Space of PBHs

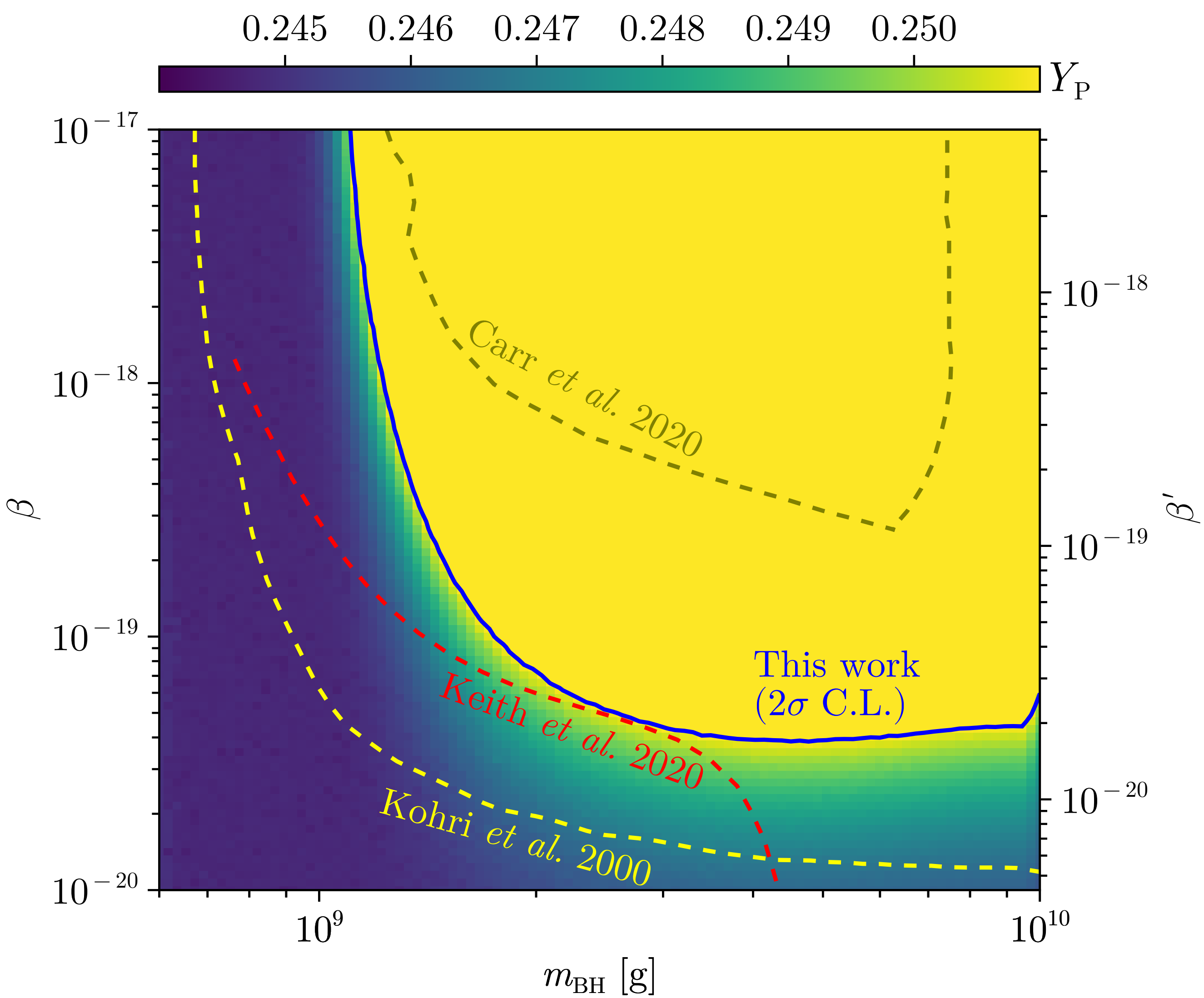
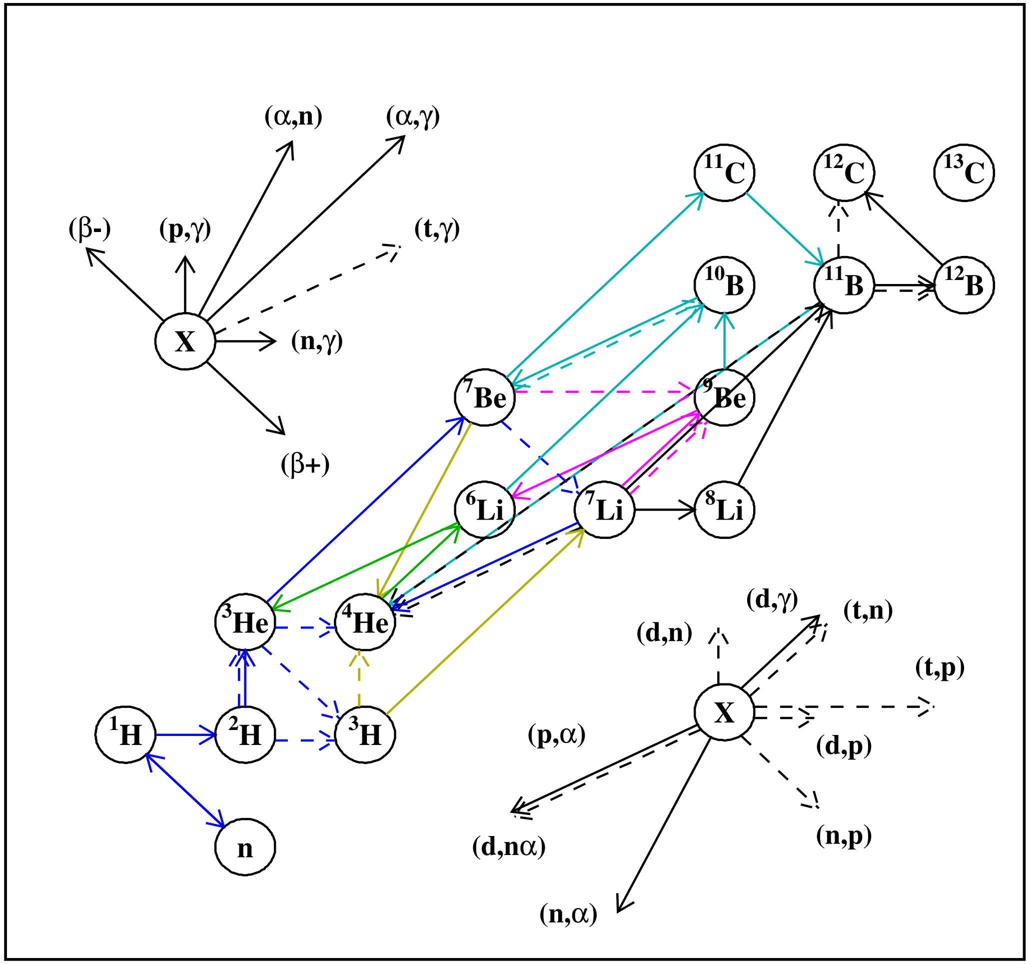



Figure 15: Our constraints on PBHs from BBN. Code available at https://github.com/Fenyutanchan/Primordial-Black-Holes.git.

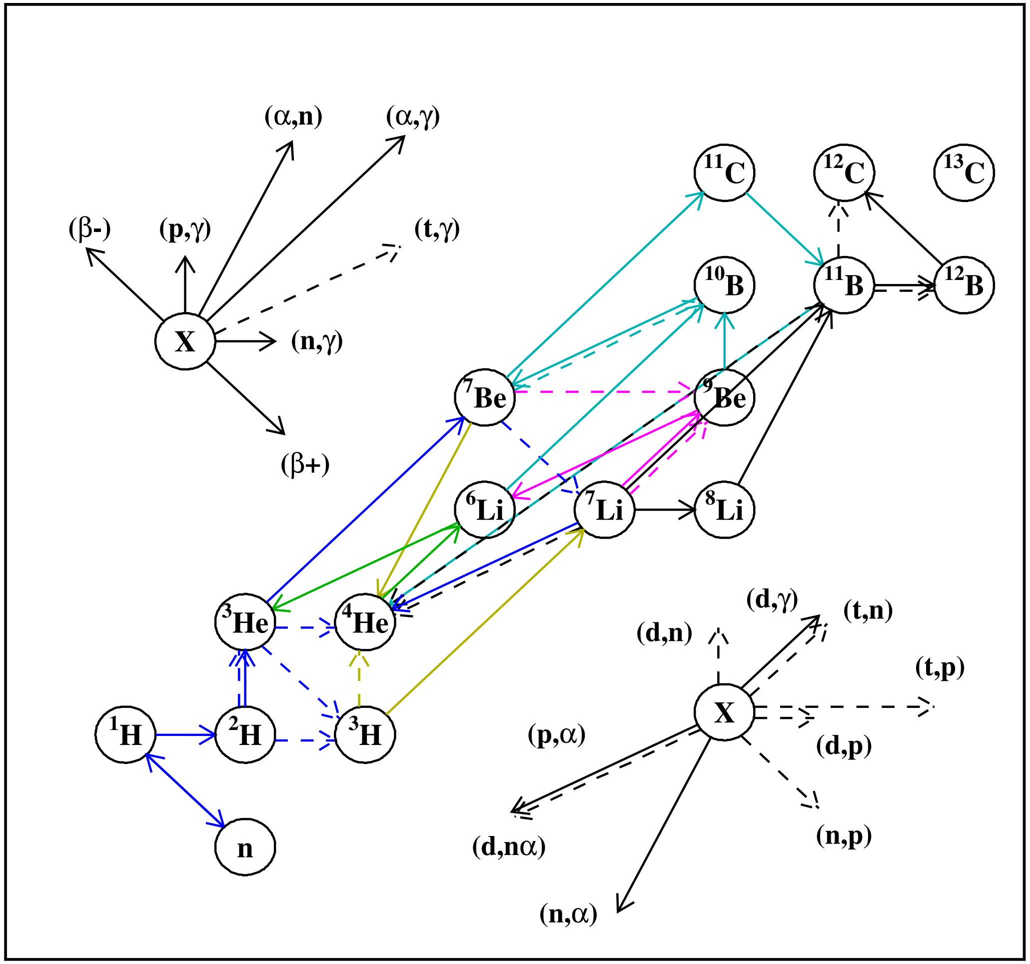
# Outline

# 4.1 How New Physics Affects BBN?




- **Affecting the ingredients:** $X_n$;
- **Affecting the background:** $H$, $N_{\rm eff}$...
- Affecting the nuclear reactions...
- Affecting the results of BBN...

# 4.2 What's Next?




- **Ongoing:** Complete nuclear network for BBN should be implemented.
- **Ongoing:** Dissociation effects from new physics should be included.
- **Ongoing:** More dark scenarios...

# Acknowledgements

*Thanks for your listening!*

# References

## References

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